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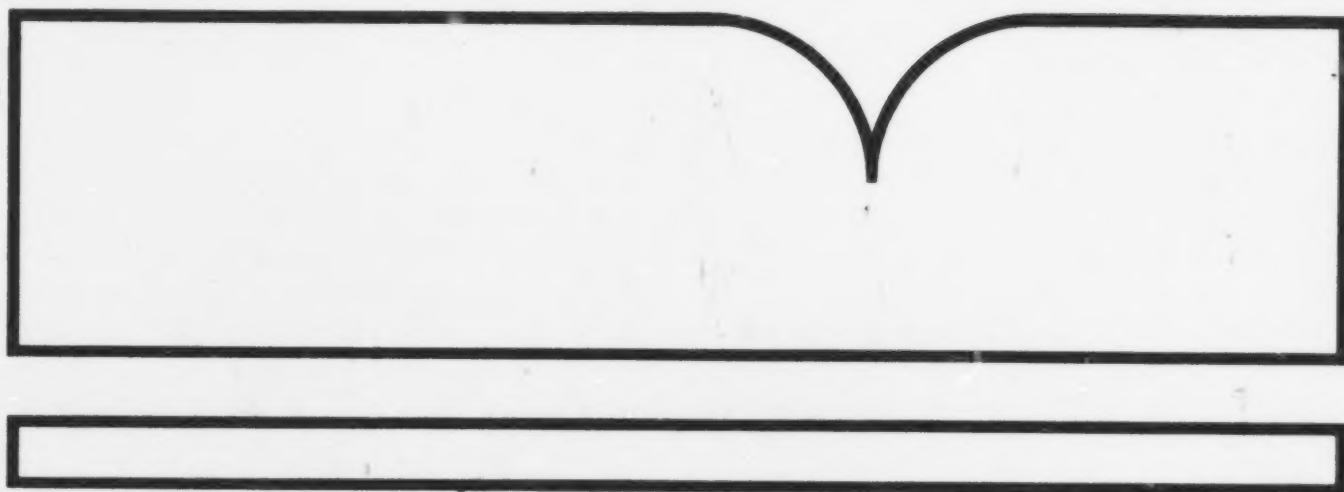
Development of a Charged Grid
Sensor for Airborne Carbon Fibers

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DEVELOPMENT OF A CHARGED
GRID SENSOR FOR AIRBORNE
CARBON FIBERS

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16. ABSTRACT This development addressed the sensing and measurement of carbon fibers moving in ventilating ducts or the exhaust stacks of incinerators. The sensor system utilizes a series of 5 electrically charged grids with different grid spacings to sense the fibers, make determinations of their length, and present a count of the numbers detected. The system will sense carbon fibers shorter than 0.1 mm moving at velocities from 2 to 4 meters per second. In addition, the system will measure fiber populations up to 100 fibers/meter³ in each of 5 lengths ranging from 0.1 mm to 1.5 mm. The areas which require further development have been identified together with a list of design requirements and alternate materials or fabrication techniques applicable to producing a unit for evaluation in a field test. A companion development produced a mobile flow test facility for evaluating and calibrating instrumentation which measures fibrous aerosols.		
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ABSTRACT

These developments address the design and testing of an instrumentation system intended to provide a continuous monitor for sensing and counting airborne carbon fibers moving in ventilating ducts or the exhaust stacks of incinerators. The system employs a tandem series of 5 electrically charged grids to sense and measure fibers in terms of numbers and the lengths of the individual fibers moving in the stream. The shortest length measurable has been established at less than 0.1 mm. The system consists of three major elements: the 5 grid sensor which mounts in a duct; circuitry to charge the grids; and circuitry to sense, count, print out and control the operation. The system has been developed to the point of an operating demonstration which has established the present capabilities and identified the areas requiring further development.

The present unit can sense and count carbon fiber populations up to 100 fibers/meter³ in each of the 5 length ranges 0.1 mm to 0.2 mm; 0.2 mm to 0.4 mm, 0.4 mm to 0.8 mm, 0.8 mm to 1.6 mm and 1.6 mm to 3.2 mm. The sensor operates efficiently when the velocity in the ventilating duct is between 2 m/sec and 4 m/sec. The principal developmental improvements required are identified as: improve the counting rate by modifying the sensing electronics; improve low velocity performance by controlling fallout and deposition within the instrument; and improve high velocity performance by changing the flow passage configuration through the electrodes of the grids.

The design studies included an evaluation of materials and construction techniques, such that a compilation of both design requirements and construction alternates have been defined.

A companion effort included the development and operating demonstration of a mobile flow test facility to support evaluation and calibration. The test section has dimensions comparable to those in ventilating ducts and the system can operate at velocities up to 11 meters per second. Fiber populations can be introduced with carbon fiber populations of 1000 fibers/meter³ achieved. Populations achievable for other fibers (such as textile) have been estimated at 100 fibers/meter³.

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1.0 INTRODUCTION

The selection of a measuring system based upon electrically charged grids applied a well established technique to the requirements of a continuous monitor instrument for carbon fibers emitted from stationary sources and moving in ducts or stacks. In previous NASA efforts (1) charged grid sensing systems had been developed into reliable, effective instrumentation for detecting and measuring airborne carbon fibers. The NASA applications focused upon that portion of the population considered a potential hazard to electrical equipment (i.e. fiber lengths 1 mm and longer). Charged grids had performed effectively in sensing as-manufactured fibers in laboratory or chamber testing (2), as discrimination and in-situ measurement of resistances for fibers moving in the plumes from pool fires (i.e., simulation of an aircraft accident) (3), and measurements of the fiber populations released during the operations associated with refuse-derived fuel (4).

The application of charged grids to an in-duct monitor instrument required the extension of the sensing capability to include fiber lengths of 0.1 mm or less. A system which appeared workable consisted of five grids in series with each grid tailored to sense a specific range in the length of the fibers (See Figure 4-1). In operation, electrical discharges from the grid wires would eliminate fibers from the gas stream; the combination of spacing and applied voltage would establish a threshold length such that all fibers longer than the threshold length would be removed from the stream and sensed by that grid. The last grid in the system would have a threshold length less than 0.1 mm. The development of the system encompassed three major objectives described as:

A. Configure and demonstrate a prototype

The prototype must use materials compatible with the environments in ventilating ducts and the exhaust stacks of incinerators. The operating demonstration must be sufficient to identify the developments required to configure a field-testable unit.

B. Evaluate alternate techniques for manufacture of the grid system

The alternate techniques would include those evaluated in the selection process leading to the design of the prototype, plus any which appear to have merit based upon the experiences with actual fabrication and testing.

C. Prepare a test facility for calibration and evaluation of Instruments

The test facility must have the capability to simulate the velocities and mass flows associated with ducts and stacks. In addition, the facility must have the capability to introduce fibers into the air stream in controllable quantities and with pre-determined lengths.

The following sections address the principal concepts and the results pertinent to each of these objectives. Section 2 presents the general conclusions and results from the development effort. Section 3 describes the areas which require focused development, Sections 4, 5, and 6 respectively describe the 5-grid sensor system, the alternates, and the flow facility.

2.0 CONCLUSIONS AND PERTINENT RESULTS

The three principal objectives of the development effort were met. A prototype 5-grid unit was designed, built, and tested. The efforts to configure a system required an evaluation of alternate techniques for manufacture. The system was tested operationally in a flow facility which could simulate to the conditions of ventilating ducts or stacks and controllably inject a fiber population into the gas stream. The results from the effort support the general conclusion that a charged grid system can be developed into a continuous monitor instrument. The pertinent supporting results may be summarized as follows:

A. Prototype Demonstration of Operation

A 5-stage electrically-charged grid sensor will operate over a usable range of flow velocities and airborne fiber populations with a minimum length for sensing of less than 0.1 mm. The present instrument will operate effectively over a range of duct velocities from 2 m/sec to 4 m/sec. Operations at lower velocities are influenced by fallout; operations at higher velocities may not allow sufficient time for a fiber to align with the field and precipitate a discharge. Each of the grids appear to sense accurately when the population of fibers range from 10 to 100 fibers/meter³. The present upper limit to the population relates to the sensing rate designed into the electrical operation of the system. At higher populations the grids can "saturate" from multiple contacts and allow fibers to pass undetected.

B. Evaluation of Fabrication Techniques

The prototype unit was successfully fabricated from materials considered compatible with the flow environment at the exit of an incinerator which employed an active particulate control system (the design effort did not consider controlled air-with-after-burning incinerators which could have exhaust temperatures that exceed 540°C). The configuration utilized Type 304 stainless steel for the grids, Teflon* for the grid supports and interelectrode insulator with Sauereisen #8** cement for both the interelectrode insulation and grid retention system. The studies leading to this configuration showed that either the chromium-nickel or chromium-nickel-iron alloys were required for grid materials. A number of ceramics or cements showed properties suitable for structure or insulators. Fabrication can utilize conventional machining techniques; however, electrical connections may require non-standard techniques for joining.

*Registered Trademark for polytetrafluoroethane as manufactured by the Dupont Co.

**Registered Trademark Sauereisen Cements Corp.

C. Flow Simulation Facility

A recirculating wind tunnel was designed and built as a mobile self-contained facility for evaluating and calibrating fiber sensing instruments under conditions which could simulate the flow velocities associated with ventilating ducts or exhaust stacks. The unit provided flow velocities which covered the range which would be encountered in industrial operations. The test section of the flow facility had dimensions comparable to actual ducting and would allow operation of an instrument under simulated free-stream conditions. The system for introducing and maintaining a fiber population operated to provide repeatable fiber populations. As presently configured, the flow facility can provide velocities ranging from 0.3 m/sec to 11 m/sec. Fiber populations of more than 100 per cubic meter appear within the capability of the system for a wide range of fibrous aerosols.

3.0 RECOMMENDATIONS; AREAS FOR FURTHER DEVELOPMENT

The construction of the prototype, followed by operation and calibration, have identified eight areas which will require focused attention in any further effort to develop a continuous monitor instrument. The degree and focusing of the effort will relate to the operating requirements imposed upon the system. The present operating requirements are summarized as:

Flow velocity - 1 m/sec to 15 m/sec

Temperature range - 0°C to 160°C

Fiber sensing length - 0.1 mm up to 10 mm

Fiber population - 1.0 fibers/m³ to 1000 fibers/m³

The airstream includes populations of dust lint and similar particulates with less than 15 mg/m³ total, and 5 mg/m³ for respirable-size particles.

In responding to these criteria, the development requirements are summarized in terms of System Operating Developments (4 items), Materials and Manufacturing (2 items), and Flow Facility Considerations (2 items).

A. System Operating Developments

1. Fiber Population Sensing Rate

The sensing of Fiber populations needs extension beyond the present limit of 100 fibers/meter³. The prototype unit as configured would show a fiber counting rate approaching 60 per second if it were to operate in a flow velocity of 15 m/sec and a fiber population of 1000 fibers/m³. It is recognized that 1000 fibers/m³ is a high population for any ventilating or exhaust system involving a particle control element (e.g., a filter or electrostatic precipitator). The principal area for evaluation is the trade study that balances the energy needed to consume the fiber in relationship to a maximum repetition rate and the electrical circuit technique for quenching the arc and reestablishing the field strength. The energy requirement to consume fibers has been well established by measurements and falls within the range 0.5 to 1 watt/cm (6). The present technique utilizes a capacitor discharge to supply the energy. A resistor in the recharging circuit limits the current and quenches the arc. Recovery time to full field strength is determined by the size of the capacitor and the value of the resistance. Other more complex switching and charging techniques can be employed. The need must be balanced against the operating requirements of the instrument expressed in terms of the counting rates for each grid.

2. Sensing Capabilities

The sensing capabilities must be extended upward in velocity range. At in-duct flow velocities above 3 meters/sec the present unit does not appear to complete the alignment/burn-out/sense sequence. The electrodes in the present system utilize circular cross-section Type 304 stainless steel tubes 0.030 inch in diameter (hypodermic needle stock). The length-of-path at full design field strength is relatively short. As a consequence, there appears an upper velocity threshold which will allow a 90 degree rotation and arc breakdown for the worst-case, randomly oriented fiber entering the grid. The suggested approach would be to shape the grid electrodes and provide a longer passage through the area of maximum (e.g., design) field intensity. A flow passage length equal to 5 times the spacing between electrodes would be considered a minimum appropriate compromise.

3. Flow Field

A series of charged grids will perturb the local flow field. A technique specific to the installation may be required to assure the equivalent of an isokinetic sampling. For applications to ventilating duct systems, a small boost fan at the exit could provide an isokinetic inlet. The flow perturbation can be reduced by selection of grid materials to employ thinner sections (other than 0.030 inch diameter tubes). In addition, the flow areas through the grids can be equalized by increasing the passage sizes. One approach could utilize a radial outflow for the active sensing area. The configuration of the instrument then has a small diameter (5 cm) inlet with a 10 cm exit diameter. The cylinder-cone-cylinder shape would provide aspiration. This concept has been successfully employed in sampling from fire plumes under the name "Peterson Samplers" (3).

4. Contaminants in the Air Stream

The voltage associated with the charged grids produce an effect similar to an electrostatic precipitator in relation to other less-conductive materials moving in the gas stream. An operational instrument will need a positive means for removing the dust particles which will adhere to the grids. The need will be most critical for the small-fiber sensing grids. In operating the prototype units, a reverse blast of air provided the degree of cleaning needed to continue testing. The definition of requirements for a cleaning system should reflect a knowledge of the materials which would have to be removed as an input to the design study for the technique. The technique selected for experimental evaluation should

include both air blast and mechanical systems. The option to retain either approach should be reserved until the applications for the instrument become defined.

B. Materials and Manufacturing

5. Triboelectric Effects From Insulating Materials

The selection of Teflon as the supporting structure and principal electrical isolator for the grids identified a developmental area relative to the material employed to define the walls of the flow passages. In addition to having excellent dielectric properties, Teflon also exhibits strong triboelectric effects. Airflow over the surface appears to induce a static charge so that fibers stick. Test operations revealed a heavy build-up and entrapment of fibers on the walls of the flow passages between the grid stages. The selection of materials for application to the walls of flow passages needs to address the apparent triboelectrical effects as well as the insulation capabilities. The process of defining the liner for the flow passages should include an evaluation of metallic elements which are also charged. The presence of a modest, uniform electric field in the flow passages between the grid stages could serve to pre-orient fibers so that the efficiencies of the sensing fields could be improved.

6. Material Selections and Manufacturing Techniques for Charged Grids

The individual electrodes of a charged grid must be structurally capable of operating under the aerodynamic loads of the flow field with no auxiliary support (e.g. tension) beyond a simple beam attachment. The surface must show oxidation resistance without generating a significant electrical contact resistance. In addition, the electrodes must be thermally stable against both the temperature of the air stream and the local heating caused by a fiber-induced arc breakdown. Practical considerations limit the candidate materials to the 80 Ni-20 Cr alloys (Nichrome*) or the Ni-Cr-Fe alloys such as the 300 series stainless steels. These alloys are available in shapes compatible with applications to electrodes; the requirements are for straight drawn (not coiled), unannealed (work hardened) sections. The development efforts therefore must address the following items.

- (a) Procurement of hard, straight elements with the proper cross sections for electrodes. This effort could result in a special production run by a supplier.

*Registered Trademark of the Driver Harris Corp.

- (b) Methods to provide position alignment and spacing during insulation and joining to the external power (charging) leads.
- (c) Evaluating the available insulating materials, moldable ceramics, and spray coating ceramics as inter-electrode insulators or grid support members.
- (d) Evaluation of joining techniques between the grid electrodes and the exterior power supply leads. The joining technique must not upset the work hardening of the material since most nickel alloys cannot be quench or precipitation hardened. The alternate technique should include silver solder, electroforming, and mechanical joining such as swaging or crimping. (Furnace brazing is not considered acceptable).

C. Flow Facility Considerations

7. Fiber Length Limitations

The chopper utilized to cut fibers for injection into the air-stream of the flow facility represented an extension of capabilities for a unit designed in support of NASA-sponsored in-chamber testing (2). The unit employs a stepper motor driving two wheels as the means for advancing a multi-fiber strand (tow) a precise distance. A solenoid-driven guillotine makes the cut. The unit will make precise repeatable cuts on a 3000 strand tow down to lengths of 0.2 mm. Further development is required to achieve similar cutting at 0.1 mm. The developments required are within the capability of the guillotine cutter. The efforts will involve the shaping of the cutting edges, tolerance control of the moving member (blade), and operation with a smaller number of fibers in the tow. A precision feed of 0.1 mm has been obtained with the present system.

8. Velocity Control System for the Facility

At present, the drive system for the flow facility utilizes two 1.5 hp variable speed dc motors belted to the shaft of a fixed-pitch fan. The system can attain test velocities above 12 m/sec; however, the load sharing between the motors is unsatisfactory. A change to a single motor drive is considered appropriate. The tunnel drive should utilize a system based upon silicon controlled rectifiers and a voltage-controlled, series-wound, direct-current motor rated at 5 horse power. (The dual motor concept was based entirely upon availability of 1.5 hp motors from previous carbon fiber studies).

4.0 PROTOTYPE INSTRUMENT CHARGED GRID SYSTEM

The charged grid system consists of three major elements as the grids, the charging power supply, and the sensing-counting circuitry. For each of the elements, development continued throughout the design and evaluation testing efforts. The descriptions of these efforts are presented in terms of the concepts and designs followed by the results of evaluation and calibration testing.

4.1 Concepts and Designs

The concept and design of the grids drew upon experimental data and operating experiences at The Langley Research Center (2) and at the Jet Propulsion Laboratory (5).

4.1.1 Prototype Instrument System Concept

The operating concept for the instrument system is based upon experimental data which measured the burn-out of carbon fibers between charged electrodes. For fibers which contact the electrodes, burn-out could be assured at field strengths of 2000 volts/cm (2Kv/cm). A field strength of 10 Kv/cm would precipitate an arc breakdown burn-out for fibers of lengths equal to half the distance between the electrodes. The current required to burn-out a fiber had been measured and ranged from 10 milliamperes upward, with 30 milliamperes assuring the burn-out of any fiber (6).

These results led to the concept of five grids operating in series with each grid sensing and eliminating a specific range of fiber length. Figure 4-1 illustrates the system concept. The NASA experience with fibers emitted from pool fires, and with the measurements of fibers passing through the air filters in ventilating systems, had shown that an upper practical limit for fiber lengths was in the range 3 to 4 mm. Data from the processing of carbon fiber composite scrap mixed in refuse-derived fuel had further confirmed an upper practical limit in the range of 3 to 4 mm for lengths of fiber released. All of the measurements from fiber releases showed the major portion of the population to have lengths below 1 mm. A practical average length for those fibers longer than 1 mm was established as 1.7 mm (7).

In consideration of these data, a 5 stage grid system could cover the length range from 0.1 mm to 1.6 mm by sensing in length ranges which correspond to factors of 2. The exit grid would measure fibers in the length range 0.2 mm to 0.1 mm with a threshold length below 0.1 mm. The inlet grid would sense and eliminate all fibers longer than 1.6 mm.

The individual grid stages would be configured to operate at either 2 Kv/cm for a contact burn-out threshold, or at 10 Kv/cm for an arc breakdown threshold.

The energy to consume the fiber would be stored in a capacitor located at each grid; the capacitor would be recharged through a resistor of value such that the recharge current would not sustain an arc.

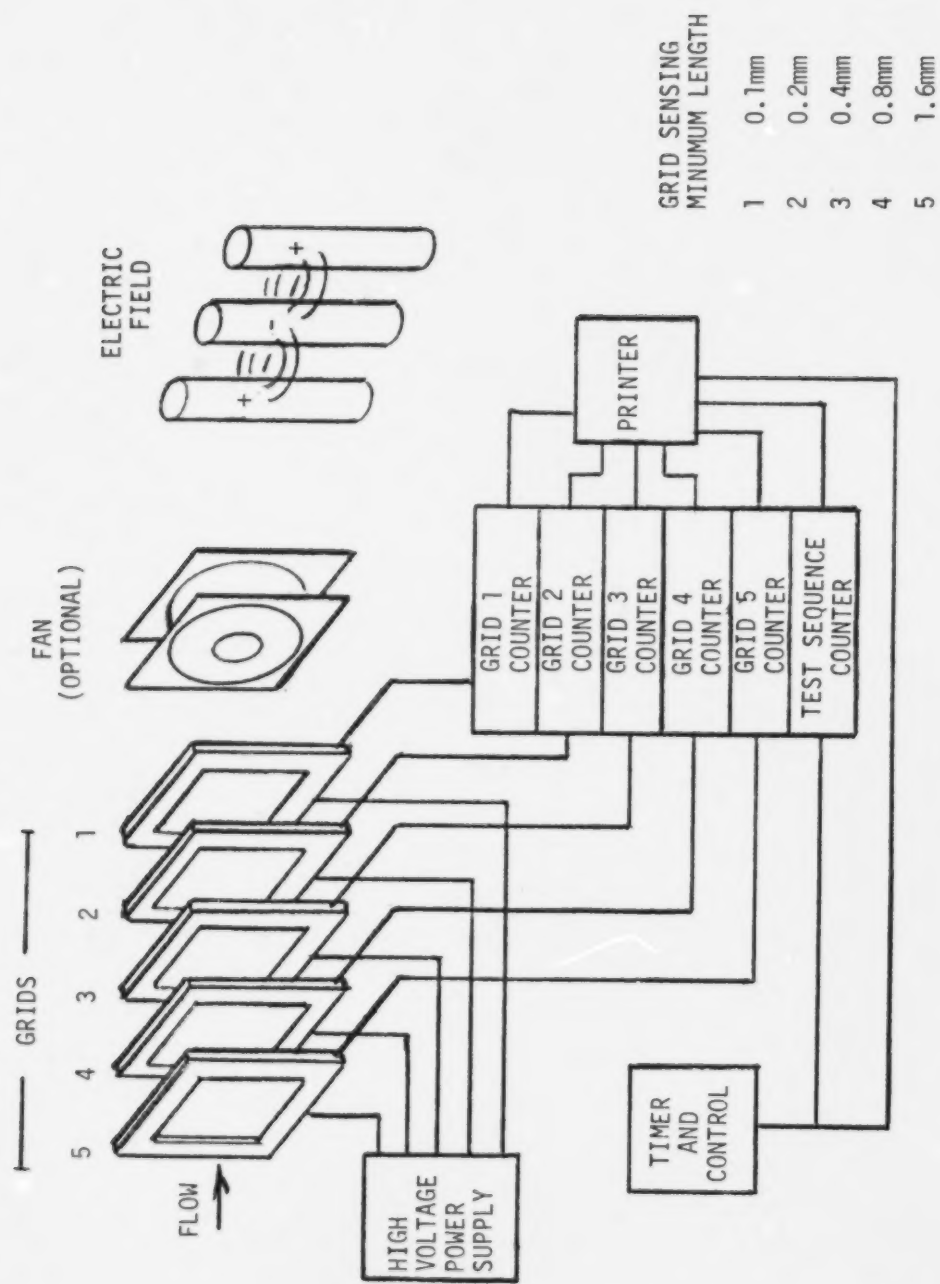


Figure 4-1. Concept Schematic Diagram For the Charged Grid Sensing and Measuring System.

The discharge of the capacitor would provide a triggering signal to a sensing circuit which fed a counter. The events at each grid would be counted separately; the system, therefore, would make length discrimination measurement as part of the total count. A timer circuit would provide a means for relating the counts at each grid to a population of fibers moving in the air stream. Thus, for any set of flow conditions, the system would determine the presence of conductive fibers in the stream, provide a measurement of the length distribution and, over a period of time, establish an average volumetric population for the fibers moving in the stream.

4.1.2 Design of the Grid Elements

The design of the grid elements encompassed the sensing geometry in terms of a material for the electrodes, a method for supporting the electrodes, an interelectrode insulator, and a means for electrically charging the electrodes. Table 4-1 summarizes the design conditions established for the grid system. The length of fibers to be sensed at each stage established the air gaps which, together with the mode of sensing, determined the field strengths and corresponding voltage applied to the electrodes. Practical considerations limited the smallest air gap to 0.2 mm, and dictated the use of an arc breakdown mode for sensing in the last two downstream grids. The combination of fiber length and voltage available served to establish the value of the capacitor such that the arc pulse energy would consume the fibers. Early measurements had established a pulse energy value of 100 millijoules per centimeter of fiber length (6). Subsequent work showed the value excessively conservative. The overall sizing of the prototype led to selecting flow passage dimension of 5.08 cm by 7.62 cm (2 in. by 3 in.) as a practical compromise. As a minimum condition, a flow velocity of 1 m/sec through the 0.2 mm spaced grid³ would average one count every 13.5 seconds for a population of 10 fibers/m³.

The configuration of the individual grid assemblies and the integration of the 5 stages into a unit took advantage of known materials and known material requirements. Testing in the laboratory and testing in the plumes of pool fires had established the alloy requirements for electrode materials. The selection of Type 304 stainless steel reflected a ready availability from hypodermic needle stock for a straight, hard-drawn tubular form. The selection of Teflon for the structure represented a knowledge of its operating temperature limits, its insulating properties, and the dimensional tolerances achievable during machining. Teflon is readily available as half-inch-thick sheet stock. The final details of the grid units are shown in Figure 4-2; the assembly of the 5 grid sensor unit is shown in Figure 4-3. The features of the unit which represent the culmination of a development effort are:

A. Interelectrode Insulation and Electrode Retention

The interelectrode insulator had to provide a dielectric capable of withstanding the field and at the same time accommodate the thermal differential expansion between stainless steel and Teflon. The principal dielectric is supplied by heat shrinking Teflon tubes over the ends of the electrodes; such tubing was available with a

TABLE 4-1. GRID SYSTEM DESIGN SUMMARY

A. Fiber Sensing Parameters

Grid	Air Gap mm	Field Kv/cm	Sensing Length Range, mm	Sensed By
1	0.2	10	Less than 0.1 to 0.2	Arc
2	0.4	10	0.2 to 0.4	Arc
3	0.4	4	0.4 to 0.8	Contact
4	0.8	2	0.8 to 1.6	Contact
5	1.6	2	1.6 and longer	Contact

B. Energy Related Parameters

Grid	Air Gap mm	Voltage vdc	Capacitor	Energy Stored mj	Specific E per cm of fiber mj
1	0.2	200	0.5	10	500
2	0.4	400	0.1	8	200
3	0.4	160	1.0	12.8	160
4	0.8	160	1.0	12.8	80
5	1.6	320	0.2	10.2	64

C. Flow Related Parameters

Grid	Air Gap mm	Number of Grid Wires	Flow area Sensed cm ²	Nominal Open Fraction
Free Stream			38.71	100
1	0.2	72	7.42	0.20
2	0.4	64	12.40	0.33
3	0.4	64	12.40	0.33
4	0.8	47	16.69	0.50
5	1.6	32	25.19	0.68

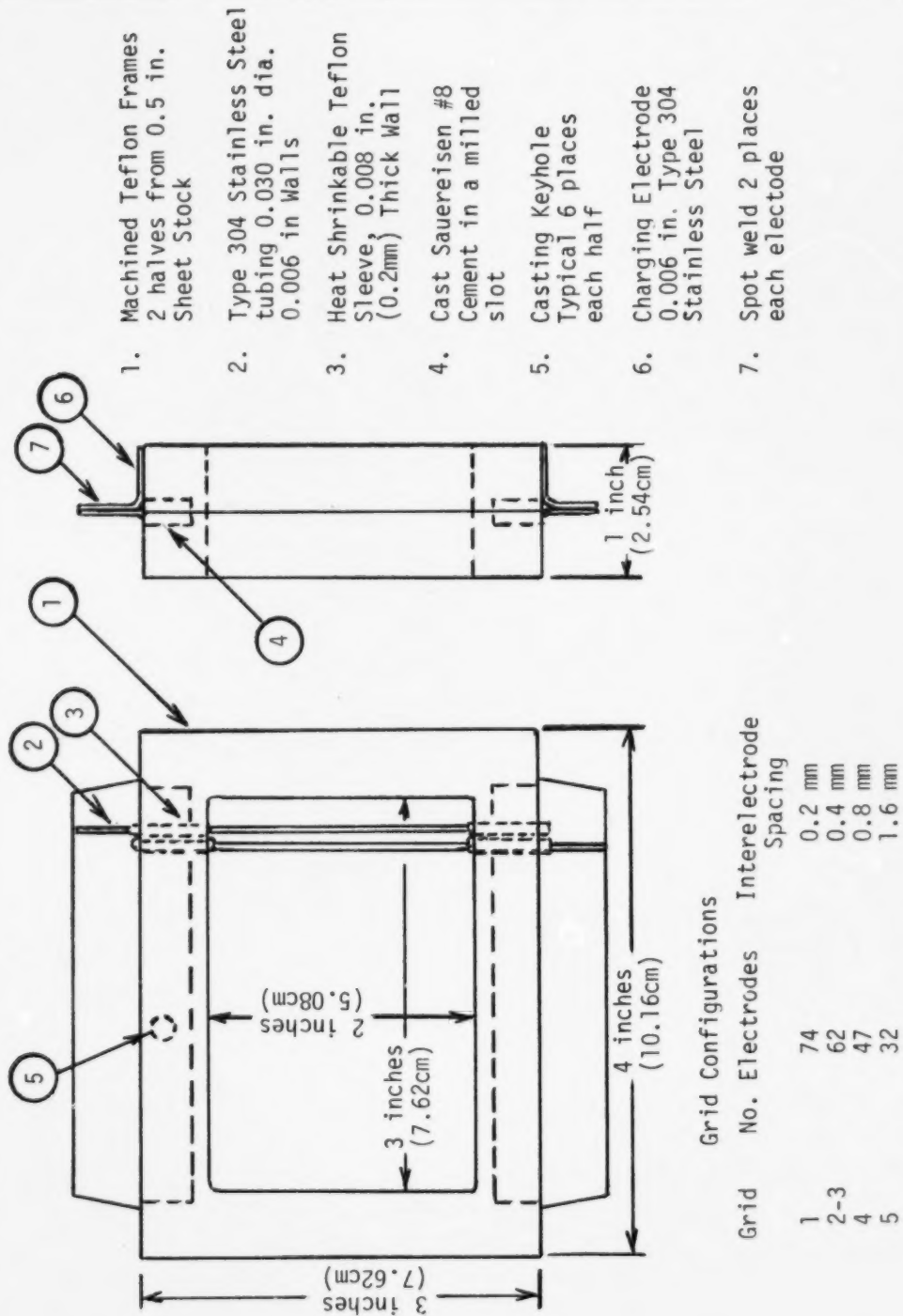


Figure 4-2. Summary of Design Features for the Charged Grids.

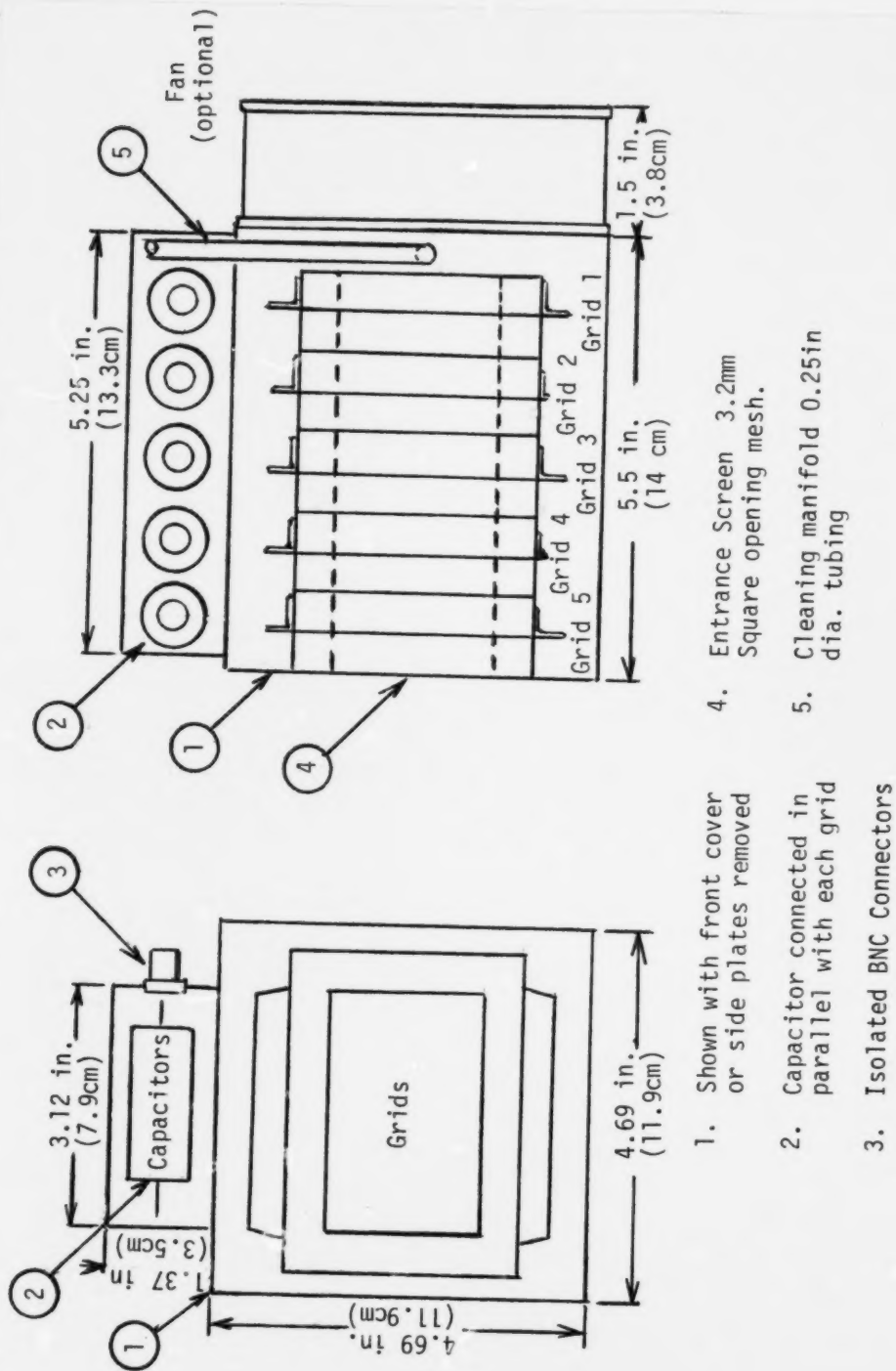


Figure 4-3. Assembly Features for the 5 Grid Sensor Unit.

thickness equal to the 0.2 mm spacing. The Teflon provided the insulation and would accept the differential motion from thermal expansions. The positive retention of the electrodes utilized Sauereisen #8 cement. The wet-castable cement provided the structural support for the electrodes and additional insulation. The cement does not adhere to the Teflon, therefore, a number of mechanically interlocking holes were incorporated into the Teflon frames.

B. Interelectrode Spacing

The electrodes must be retained in proper position for the assembly into the frames and during the application/cure of the inter-electrode cement. A stack of shims provided the means for aligning these assemblies. The stack involved alternate layers with thicknesses equal to the diameters of the tubes and thicknesses equal to the air gap between the tubes. Brass shim stock of appropriate thicknesses were readily available. The dimensional tolerances required a careful preparation of the shim pieces since the tubes had to be securely aligned for both interelectrode spacing and maintaining a plane. The results of assembly showed that the 0.2 mm spacing was within an 11 percent deviation envelope; the wider spaced grids showed a proportionally smaller percent of deviation from design.

C. Electrical Connections

The electrical connection between the individual electrodes and the external power supply utilized spot welds. The Langley Research Center had developed a technique for spot welding thin-section stainless steel as part of their developments in instrument fabrication. The welding technique was successfully applied to the grid electrodes. The welded joint is between equal thickness of Type 304 stainless steel. The electrical contact to the external power supply is mechanical (by screws) to a brass strip.

4.1.3 Design of the Grid Electrical Power Supply

The grid electrical power supply provides the discrete voltages for the grids, a current limit, a recharge capability, and the fiber sensing signals to the counter. Figure 4-4 is a schematic diagram of the circuit. A transformer-fed diode ladder provides the discrete voltages which establish the required electric fields between the electrodes of each grid. The burn-out energy is stored in a capacitor located at the grid; the capacitor receives the charging current through a blocking resistor. In operation, the combination consumes the fiber, extinguishes the arc, and recharges the capacitor within a 10 millisecond period of time. The sensing element of the circuit utilizes the voltage excursion associated with the discharge of the capacitor to produce a 0 to 5 volt pulse signal as an input to the counting system. The combination of a buffer resistor, a light emitting diode, and a resistor-to-ground generates the pulse and provides a visual indication.

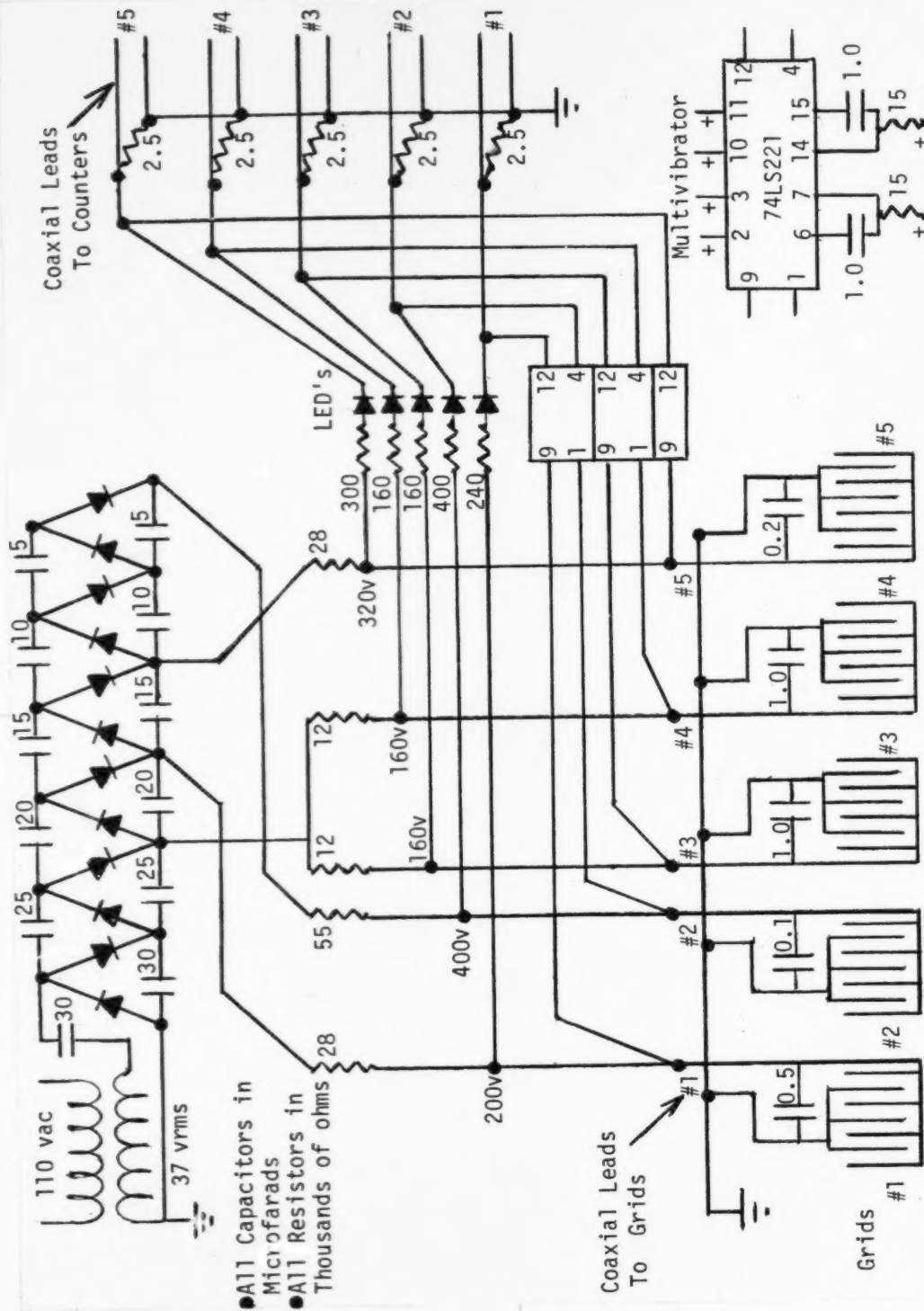


Figure 4-4. Schematic for the Grid Charging and Sensing Circuit.

The developmental operation confirmed the design, however some spurious signals did occur. The spurious signals showed the need for a trigger control circuit which was added to shape the pulse into the counter and to inhibit any further pulses during the 10 millisecond discharge-recharge cycle. The trigger and delay functions were provided by utilization of a monostable retriggerable multi-vibrator.

4.1.4 Design of the Counting Circuitry

The counting circuitry accepts the signals generated by the discharges at the grids and provides a print-out of the total number of discharges for each grid summed over a preselected period of time. The circuitry provides an active counting range from 0 to 999 for each grid and, in addition, provides a sixth counter to monitor or index the number of counting sequences performed. The time interval options available are 15 seconds, 150 seconds, and 1500 seconds. Figure 4-5 shows the overall functional flow for the system; the functional features of the principal elements are summarized as follows:

A. The Counters

Within the six counter circuits, five accept input signals from the grids and one (test sequence) obtains its input from the control circuits (See "C" below). The circuit configuration for all six counters are identical and are based upon standard digital microcircuits. In operation, the input pulses feed into a triggered inverter (74LS14) as a conditioner before entering into decade up counters (74LS90). Three counters in tandem provide and hold counts from 0 to 999. The circuit includes an overflow protection which retains the saturation count of 999. Thus a 999 reading becomes an indication for an incomplete measurement. The stored count is sensed and fed into the printer section through digital interface elements (one for each decade) consisting of serial-fed, sequence-read, eight-bit shift registers. The data input to the printer is in the form of a binary coded decimal (BCD). The counters cover five circuit boards. The decade up-counters sections are placed three-on-a-board with the number one element as the test sequence monitor. The digital interface shift register sections are placed one-on-a-board with each board providing one of the output digits from each of the six counters.

B. The Printer

The printer element is a commercially available Datel unit Model DDP-7. The unit has been designed to accept the output of a shift register as a binary coded decimal and has the capability to print six channels sequentially on a thermal paper roll. The unit generates interface signals for control purposes, selection of channels, and for the formatting of results. In addition, the unit has a capability for an internal operating check which can exercise the printing logic and printer. The printer is installed as self-contained unit within the circuitry package.

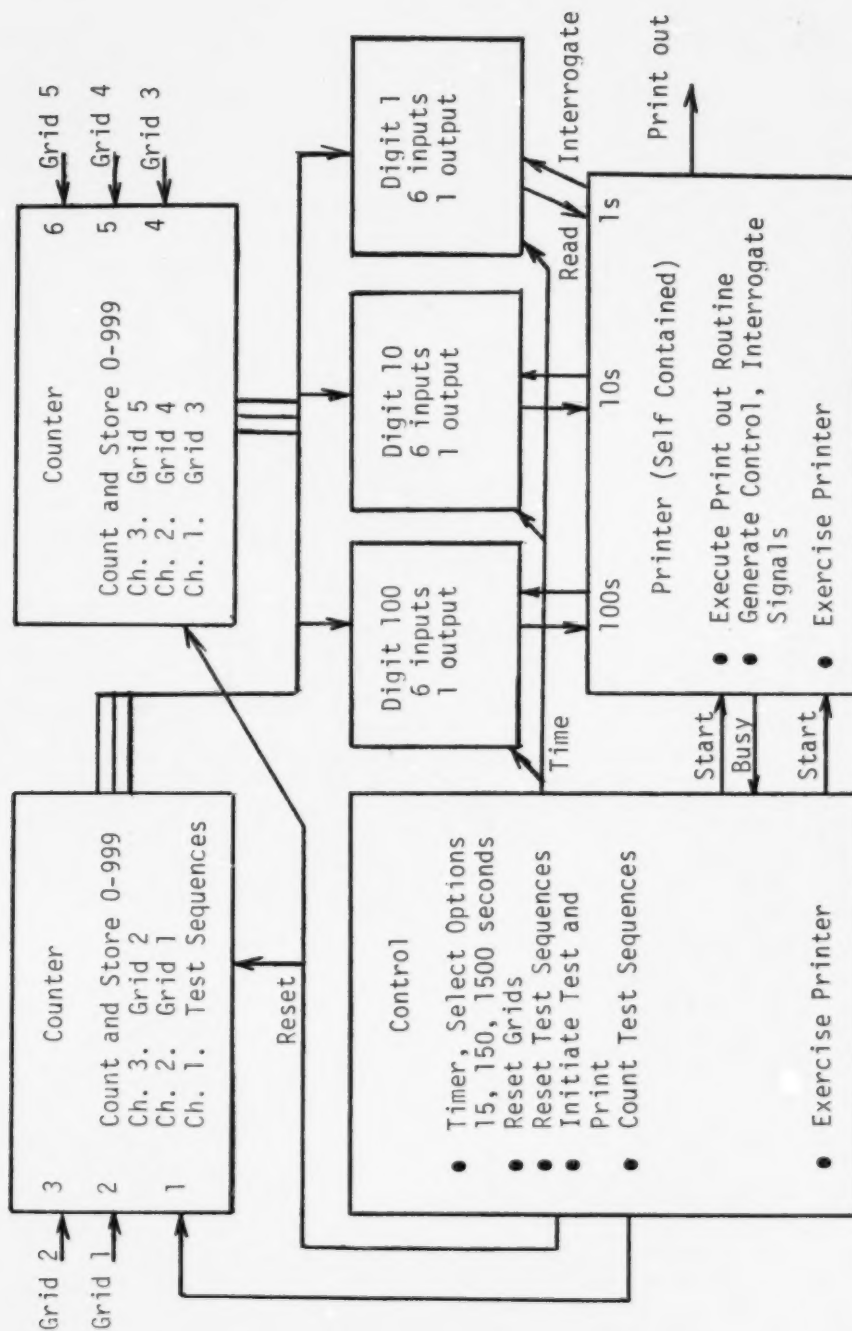


Figure 4-5. Functional Elements of the Counting and Printing Circuitry.

C. Control and Interface Circuitry

The control and interface elements provide the initiation and timing for the counting intervals plus the logic control signal for the readout of the counters into the printer. The principal operating element within the control circuitry is a 15 second timer based upon a standard microcircuit element. (555). The timer achieves a 150 second and a 1500 second capability by feeding through one or two decade counters. The output of the timers are controlled by a timer select switch. In counting operations, the counting time option is selected and the sequence initiated. The initiation clears all the fiber counters to zero and has the option to clear the test sequence counter to zero. At time-out, logic circuits based upon monostable multivibrators and gates initiate the print sequence. The printer interacts with the control to generate the signals necessary to read the counters and execute a print out. These circuits involve an additional multivibrator and inverters. Within the circuitry package, the control and interface elements are mounted on one circuit board.

4.2 Results of Testing and Evaluation

The evaluation and calibration testing established the operating capability for the system and identified the directions for further developmental effort. The testing consisted of bench evaluations which did not produce quantitative data, and operations in the flow simulation facility which were intended to generate quantitative measurements.

4.2.1 Operational Evaluation Testing

The operational evaluation testing addressed the burn-out of fibers at the grids; the ability of grids to respond to the length ranges intended by design; and the responses of the system to a flow of fibers. These tests were performed in a flow passage on a bench top or within a small chamber. An exit fan (see Figure 4-1) provided the flow velocities and this fan was calibrated in terms of operating voltage as shown in Figure 4-6. This calibration served as the base for subsequent comparisons. The principal observation and results from these evaluation tests included the following:

A. Burn-out of Fibers

A grid discharge which either cut a fiber into segments or shortened a longer fiber could introduce errors into the counting of the fiber population. Such an effect would require a statistical correction to the counting results before the data could be accepted as a measurement. The effect had not appeared during chamber or fire-release testing; nevertheless operational verification was considered necessary for the 5-grid sensor. In the evaluation, small quantities of pre-cut fiber were introduced into the grids while they operated with a fan induced flow. In this mode, cutting or partial burning at the front grids (grids 5, 4) would be followed by counts at the downstream grids (grids 2, 1),

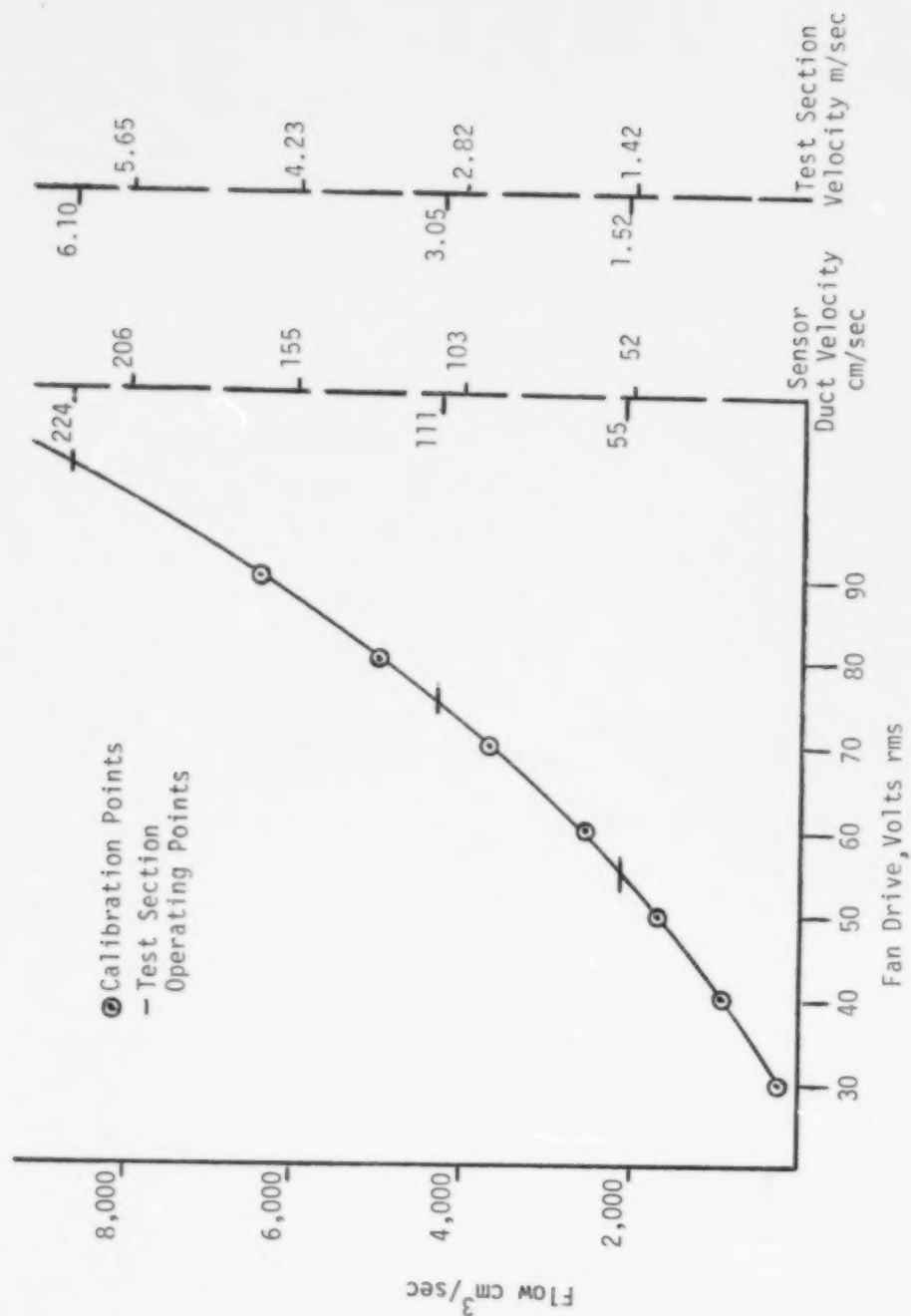


Figure 4-6. Flow Characteristic For the 5-Grid Sensor.

and possibly short fibers (less than 0.1 mm) collected on a filter downstream of grid 1, (and upstream of the fan). Operation with fibers having lengths greater than 0.8 mm (grid 4 spacing) did not produce any downstream counts (grids 2, 1) or show any fiber residue collected on the filters. These operations indicated that any fiber which precipitates a discharge will be consumed.

B. Fiber Length Discrimination and Sensing

This series of evaluations was performed in a small chamber with airflow through the instrument induced by the exit fan. Single fibers were lofted by means of a pulsed air jet blowing through a clump of fiber pre-cut to lengths of 3 mm (long), 1 mm (medium), and 0.5 mm (short). In qualitative testing the grids responded according to the length spectrums contained in the cut fiber.

Evaluations and inspections of the grids indicated three effects were compromising the operation of the 5-grid sensor. Fibers were adhering to the Teflon walls of the flow passages between the individual grids; fibers were contacting the grids before the recovery time had been completed, and there was evidence that, at the higher velocities, fibers could pass through the field without making contact or precipitating an arc. The fallout of fibers by adherence to the Teflon is a materials-related effect, and indicates a need for a modification to the surface selected as the liner for a flow passage. The other two effects were recognized in the design of the grid.

If a grid receives a number of near-simultaneous impacts, the first fiber will burn but the subsequent contacts can provide a conductive path capable of accepting the recharge current without a burn-out. In such a "saturation case" when the grid does not recover to full voltage, and the counter then operates at 100 per second until it stops at 999. This phenomenon was observed and placed a practical upper limit on the fiber population which could be presented to the 5-grid sensor. In addition the condition established the need for a back-blast system which sensed saturation and then proceeded to clean the grid.

The data which guided the design of these grids showed the destruction of fibers at velocities up to 6.05 meters per second through electrodes 0.6 mm in diameter. These data indicated a response time of 100 microseconds for alignment and arc response. Arc responses occur in a few microseconds, thus, the major portion of the response time relates to the orientation of the fiber within the field. In the present configuration, grid 1 would have local velocities of 6 m/sec when the free stream velocity between the grids reached 1.2 m/sec. The design of the system anticipated velocities above 6 m/sec through grids 1, 2, and 3.

C. Measurements from Chamber Testing

Preliminary quantitative measurements were attempted in the chamber. For this effort a calibration rig was constructed which had the same flow areas and flow resistances as the 5-grid sensor itself. The fan-driven calibration unit would achieve the same flow velocities at the same power settings as the 5-grid sensor while capturing all fibers on a filter element. Measurements were attempted with fiber lengths of 3 mm, 1 mm, and 0.06 mm. In these tests, grid 3 did not appear to operate properly, these data are considered valid for pairs of grids. The measurements were performed at free stream flow velocity of 0.2 m/sec. in an effort to maximize the sensitivity. Table 4-2 shows the measurements obtained. For the 3 mm fibers the population was low. The grid counts and filter counts are well within the statistical variations generally observed for fiber collections on filter elements.

When the grids were presented with a higher population of shorter fibers, the counting efficiency of the grids appeared to drop. The data show that for a count of 1000 fibers, less than 10 percent were recorded by the grid. These deviations reflect the effects of fallout adhesion to the walls and saturation of the grids.

4.2.2 Operation in the Flow Test Facility

The operations in the flow test facility continued the evaluation of length distributions and sensitivity to population at flow velocities which simulate the conditions in ventilating ducts. For these tests the 5 grid sensor unit and the calibration unit were both installed in the test section so that they were equidistant from the walls and from each other. Velocity measurements around the calibration unit showed that it passed 10 percent of the flow associated with its frontal area. The evaluation measurements were performed at duct-stream velocities of 1.52 m/sec, 3.05 m/sec, and 6.1 m/sec using cut fiber lengths of 0.2 mm, 1.0 mm, and 2.0 mm. The data from the filter in the calibration unit measured the fiber population flowing in the tunnel. (These data are presented separately and discussed in Section 6.2 and Table 6-2). The grids operated and provided data; the problem experienced with grid 3 in the chamber testing was corrected by charging at 320 volts instead of 160 (4 Kv/cm). The measurements obtained from the grids are summarized in Table 4-3. The data show effects of fallout, saturation, and velocity. An overall interpretation suggests an operating regime where extraneous effects are not significant and, within the regime, the system could measure effectively. Each of these considerations are addressed below.

A. Estimate of a Usable Operating Regime

A survey of the data shows cases where the individual grids appeared to count all the fibers presented within that segment of the total population. These cases occur at velocities of 3.05 m/sec and at populations below 100 fibers/meter presented to a

TABLE 4-2. OPERATING EVALUATION

FIBER LENGTH RANGE mm,	GRID COUNT	FILTER COUNT	COMPARISON FRACTION SENSED
Case 1, 3 mm Fibers			
0.1 - 0.2	2	5	Statistically equal measurements
0.2 - 0.8	24	20	
0.8 - 3.2	187	255	
Case 2, 1 mm Fibers			
0.1 - 0.2	17	102	0.17
0.2 - 0.8	81	1029	0.08
0.8 - 3.2	262	3016	0.08
Case 3, 0.5 mm Fibers			
0.1 - 0.2	52	741	0.07
0.2 - 0.8	65	3088	0.02
0.8 - 3.2	154	329	0.46

TABLE 4-3. COMPARISON OF GRID COUNTS AND DATA FROM FILTERS FROM OPERATING TESTS

FIBER LENGTH mm	GRID COUNT	FILTER COUNT	POPULATION ₃ (1) FIBERS/METER	SENSED FRACTION
Case 1, Fibers Cut Length 0.2 mm				
A. Flow Velocity 1.52 m/sec				
0.1 - 0.2	11	40560	8362	0.0003
0.2 - 0.4	13	7360	1517	0.0017
0.4 - 0.8	32	720	148	0.04
0.8 - 1.6	13	0	-	1
1.6 - 3.2	8	0	-	1
B. Flow Velocity 3.05 m/sec				
0.1 - 0.2	361	62296	7780	0.005
0.2 - 0.4	54	2468	308	0.021
0.4 - 0.8	33	129	73	0.25
0.8 - 1.6	4	-	-	1
1.6 - 3.2	0	-	-	-
C. Flow Velocity 6.1 m/sec				
0.1 - 0.2	982	32680	3112	0.03
0.2 - 0.4	102	2492	237	0.04
0.4 - 0.8	23	284	27	0.08
0.8 - 1.6	2	-	-	1
1.6 - 3.2	2	-	-	1

TABLE 4-3. COMPARISON OF GRID COUNTS AND DATA FROM FILTERS FROM OPERATING TESTS (CONCLUDED)

FIBER LENGTH mm	GRID COUNT	FILTER COUNT	POPULATION ⁽¹⁾ FIBERS/METER ³	SENSED FRACTION
Case 2, Fibers Cut Length 1.0 mm				
A. Flow Velocity 1.52 m/sec				
0.1 - 0.2	9	720	224	0.01
0.2 - 0.4	10	560	174	0.017
0.4 - 0.8	253	400	124	0.63
0.8 - 1.6	170	9360	2916	0.018
1.6 - 3.2	19	320	100	0.05
B. Flow Velocity 3.06 m/sec				
0.1 - 0.2	371	560	123	0.66
0.2 - 0.4	388	392	86	1.0
0.4 - 0.8	602	280	64	2.0
0.8 - 1.6	108	3854	790	0.03
1.6 - 3.2	10	56	12	0.8
Case 3, Fibers Cut Length 2.0 mm Velocity 3.06 m/sec				
0.1 - 0.2	83	57	14	1.0
0.2 - 0.4	157	171	44	1.0
0.4 - 0.8	180	114	29	1.0
0.8 - 1.6	56	171	44	0.3
1.6 - 3.2	31	1485	272	0.11

(1) Population predictions are based upon data presented in Table 6-2

grid. The two operating conditions where the data show the best agreement are for 1 mm and 2 mm fibers. The operations with 1 mm followed earlier operations with 0.2 mm lengths. A small residual of 0.2 mm fibers was allowed to remain in the injection duct and some short fibers were redisseminated from fallout on surfaces. For the 1.0 mm tests the tunnel was shut down only for the change-out of the filter element and a jet-blast clearing of the grids. The airborne populations represent a continuing equilibrium. The operation with 2.0 mm fibers did involve a cleanup prior to the test. These two cases can be considered as complementing partial simulations of a working environment such that the overall results suggest a usable operating regime defined as follows:

- Velocity range 2 meters/sec to 4₃ meters/sec
- Population range 10 fibers/meter³ up to 100 fibers/meter³ within the sensing length range as presented to any grid₃ (Total airborne population is less than 500 fibers/meter³).

Ventilating systems often operate over this range of velocities and the fiber populations are of the order which could be released from the handling of tow during fabrication operations.

B. Fallout Deposition Within the Unit

The 5-grid sensor shows the lowest responses to short fibers (0.2 mm) moving at low velocity (1.52 m/sec) and suggests a fallout deposition mechanism. Observations have confirmed the build up of deposited fibers on the Teflon walls; the triboelectric characteristics of the Teflon is a potential explanation. A fallout mechanism should show a reduced effect at higher free-stream velocities; the responses of the grid appear to increase by an order of magnitude each time the velocity is doubled. Therefore, any further development of charged grid systems must address the effects of attraction or fallout.

C. Saturation

Saturation of the grids during test operation was a recognized problem. Each grid counts fibers individually and is response-limited to 100 counts per second (10 ms counter interval). Multiple fiber impacts can keep the grid from recharging. The maximum recharge currents are limited to 13 milliamperes which is near the lower limit to cause burn-out of a fiber. The incidence of multiple hits with not all fibers counted or destroyed appears entirely possible. If the populations determined for 0.1 to 0.2 mm fibers are applied to the velocities within the instrument, then the average time between impact counts would show as:

Test Section Velocity m/sec	Sensor Duct Velocity m/sec	Fiber Population Fibers/meter ³	Time per count Milliseconds
1.52	0.56	8363	54
3.05	1.11	7780	29
6.10	2.24	3112	37

These times are not many multiples of the response time built into the grid circuitry. The injected distribution for fibers moving into the tunnel has been shown as uniform over a period of time (filter collection). The potential for short term population variations exists (e.g. puffs of fibers). The potential exists for a single fiber to eliminate the field while companion fibers pass undetected. Some strong evidence of this effect is shown in the case of 1 mm fiber moving at 3.05 m/sec. In this operation grid 4 should show the maximum count and compare with the measurements from filters. The response of grid 4 appears low; however the response from grid 3 appears as double that predicted from filters. It appears that fibers which escape detection at grid 4 are influencing the response at grid 3. The considerations for multiple impacts are an item needing further study for instruments of this type.

D. Velocity Effects, Flow Path

It is recognized that the flow path through the 5-grid sensor introduces local velocity changes and distortions as the flow moves through the grids. These effects are suspected as contributors to the inefficiencies and limitations within the present instrument. A change in the velocity patterns as a function of the total flow stands as a mechanism which could influence the counting efficiency. There is a concern that at higher velocities, fibers will not have sufficient time to respond to the field and thereby escape detection. These effects are items for investigation in further developments of grid type sensors. These investigations should address the configuration of the flow passages, and the times available for sensing as a fiber traverses the electric field.

4.3 Summary of Further Development Action as Indicated

The operations with the 5-grid sensor and the associated counting circuitry have identified the following areas which will need further development in applying this technique to the continuous monitoring of airborne carbon fibers in ducts or stacks.

A. Counting Sensitivity

The balancing of the circuit design parameters needs a review toward improving the response rate of the grid discharge-recharge-count cycle. This effort should be complemented by a

study of the sensor geometry to minimize extraneous flow effects and to increase the opportunity for the field to sense the fiber. The flow which moves the fiber through the sensing field should be "developed" rather than "transient" as in this case. In addition the sensor should be designed to operate with an electric field in the "arc breakdown" range rather than in the "contact" range (e.g. operate with 10 Kv/cm fields).

B. Flow Passages and Insulators

The considerations for fallout or deposition on walls need evaluation for suitable geometries and materials. The concept of a low strength "orienting" field over the flow path between grids should be evaluated for suitability.

C. Actual Cleaning and Clearing

The effects observed from saturation and the recognition that the grid must accommodate other contaminants established the need for an active clearing system.

5.0 EVALUATION OF ALTERNATE CONCEPTS FOR FABRICATION

The evaluation of alternate concepts draws upon the experience with previous operating grids, the trade studies associated with the construction of the present unit, and the operating experience with the present unit. Each area served to identify design requirements which in turn led to formulating conceptual approaches to the implementation of a design. The evaluation of alternate concepts is presented in terms of these areas of experience.

5.1 Operating Experiences with Grid Type Carbon Fiber Sensors, Design Criteria

Three charged grid systems had been built and operated during either previous or companion efforts to the design of the 5-grid sensor, each contributed to design concepts in terms of either supporting features or observed limitations. Table 5-1 summarizes the pertinent features and results from these operations. These experiences led to the generation of design criteria as a basis for evaluation of alternative approaches to the fabrication of the 5-grid sensor system.

The laboratory grids operated in a benign environment; however, grids of this general construction were in continuous operation for a period approaching two years. The operation established the features of counting efficiency and total oxidation of the fibers. The 80 Ni-20 Cr wire used as the grid electrodes operated without damage from the more or less continuous arcing. The surface oxide characteristics of chromium plus nickel appear to offer a good compromise between electrical conductivity and erosion from the arc. The annealed wire showed no resistance to a lateral deflection; as a consequence, any handling of the grids would change the spacing between the electrodes. The field test instrument required the use of grid electrodes which were structurally stable and resilient. The grids themselves were part of the instrumentation attached to a large net (circa 9000 m²) held aloft by balloons; weight was a consideration. Availability dictated the use of music wire for the electrodes. An attempt to use segments from coiled stock revealed that the curvature could not be eliminated without an additional straight-drawing operation. During the course of the outdoor field operations, moisture condensation (morning dew) on the support member would short the charging power supply; normal evaporation would eventually recover the operation. The interelectrode insulation was a recognized critical element in the design of any grid. The field experience showed the need for a resistance to any effect which would degrade the dielectric strength of the insulating materials. The integrity of the insulation becomes most critical for units intended to operate in the exhaust environment of a municipal incinerator. Test activities employing the small mobile unit served to confirm the experiences and observations from the other two grid systems. The processing of municipal refuse into recoverables including fuel involves operations which produce airborne particles and contaminants at each step. Typical operations include shredding in a hammer mill, air segregation, magnetic separation of steel, screening, and even pelletizing. Screening (trommeling) operations produce

TABLE 5-1. PERTINENT FEATURES AND RESULTS FROM OPERATING CHARGED GRID SYSTEMS

FEATURE	LABORATORY UNIT	FIELD TEST UNIT	MOBILE UNIT
Intended Utilization	Monitor and eliminate airborne fibers released in the laboratory outside a test chamber.	In-situ measurement for the electrical resistance of fibers moving in the plumes from pool fires.	Detect and measure airborne fibers released by each process step associated with Municipal refuse derived fuel (shedding, air segregation, screening, etc.).
Geometry	Active opening 18 cm by 18 cm. Two grids in series, 2 cm apart, 3 mm space between electrodes. Support frame and intermediate members.	Open edged grid 31.5 cm 19 cm. Electrodes are 9 cm long with each electrode projecting 4.4 cm from each side of a center support member to form a double edged comb. Two comb units are combined to form one grid assembly.	Active opening 6.0 cm by 8.9 cm Electrodes span the long dimension as parallel plates supported and spaced at each end. Units employed in RDF testing had 1.2 mm and 3 mm spacing between electrodes.
Electrical Parameters	Operating voltage 700, with capacitor discharge for energy source and monitor. Field 233v/cm Discharge pulse feeds into digital counter.	Shaped profile variable voltage. Fiber sensed as electrical conductance at levels which do not cause burn-out. Sensing signal ramps voltage to cause burn-out. Voltage-current trace is camera-recorded from oscilloscope. (Slope of trace indicates resistance).	Controllable from 500 to 1500v. Nominal field was 10,000 v/cm Energy by capacitor discharge sensed through a multivibrator. Unit has short recovery time and sufficient energy to burn multiple impacts. (Counter not respond to multiple impacts.)

TABLE 5-1. PERTINENT FEATURES AND RESULTS FROM OPERATING CHARGED GRID SYSTEMS (CONTINUED)

FEATURE	LABORATORY	FIELD TEST UNIT	MOBILE UNIT
Electrode Material	80Ni-20Cr wire 0.5 mm diameter, annealed. Electrodes were wound on frame under tension to produce double layer grid. Power connections to each end of the electrode wires.	Steel music wire, hard drawn, straight, 0.06 mm dia. Power connections at center of each wire by solder to metalized surface of center bars.	Rolled copper sheet cut into strip 0.5 mm thick, 9 mm wide. Power connections soldered to ends of electrodes.
Insulation	Frame and intermediate supports constructed from fiber reinforced phenolic. Contact points with wire stabilized by room-cured epoxy.	Center bar formed from glass fiber reinforced circuit board stock metalized on both sides. Metal etched to form contact pattern. Electrodes retained by solder to metalization.	Opening and grooves for electrodes machined from Teflon sheet 1.3 cm thick. Electrodes retained by mechanical interlock into machined grooves.
Airflow	Grid placed in a 30.5 cm square duct. Exit fan lofts air vertically through the grid.	Free flow field caused by the fire plume. Velocity through grid up to 6.08 m/sec.	Variable speed exit fan calibrated for air flow in terms of applied voltage. Nominal flow velocity was 0.73 m/sec.

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TABLE 5-1. PERTINENT FEATURES AND RESULTS FROM OPERATING CHARGED GRID SYSTEMS (CONCLUDED)

FEATURE	LABORATORY	FIELD TEST UNIT	MOBILE UNIT
Observations and Results			
Contributing Observations	- Collection efficiency 100%. - Carbon fibers completely consumed. - System operates unattended for extended period of time.	- Collection efficiency near 100%. - Data obtained in hot, soot laden atmosphere.	- Data obtained in atmosphere laden with shredded paper fibers and other semi-conductive contaminants. - Fibers lengths less than grid spacing detected in a heavily contaminated environment.
Limiting Observations	Grid spacing difficult to control.	- Grids shorted by condensed moisture. - Electrodes rust.	- Grid material and joining temperature limited to about 100°C. - Grid spacing difficult to control.

airborne particle populations which can reach 10^8 per cubic meter; the major constituent is damp fiber from paper. The mobile grids operated in these environments sensing carbon fibers with lengths equal to half the spacing between electrodes (0.5 mm fibers). The capacitor discharge energy storage proved ample, photographs show as many as 5 fibers burning at one time (the counter circuit did saturate). Post-test inspection of the copper grids did reveal some evidence of erosion or pitting from the arcing.

The combination of design features and experience supported the generation of requirements and criteria. The experience of building and testing the 5-grid sensor served to expand the criteria and provide the listing of alternates.

5.2 Considerations for Alternates

The identification of potentially applicable alternate techniques principally reflects the construction and operating experience with the present 5-grid sensor. The pertinent considerations and observations which influenced the identification of alternates are summarized in Table 5-2 and discussed below.

A. Grid Electrode Alloy

The Nichrome used in the laboratory grid and the Type 304 stainless steel have shown a good compromise between oxidation resistance and electrical contact resistance either to initiate a touch breakdown or to precipitate an arc breakdown. The first two alternate alloys are considered metallurgical neighbors and should be equally acceptable. If an instrument has to be configured for operation in a high temperature exhaust stack, the use of specialized alloys may be required. The 77 Ni-13 Cr-10 Fe alloys are commercially available under the name "Inconel"* and are well established throughout industry. The Fe-Cr-Al-Co series is available under the name "Kanthal"** and have primarily been used as elements in electrical resistance heaters. For these alloys, availability and shape options may be limited. In addition, these alloys present difficulties in every forming or joining operation.

B. Grid Electrode Structural Elements

The necessity to accommodate thermal cycling as part of the operating installation complicates a design based upon tension to stabilize the electrode structure. In addition the flow paths between the electrodes should have a path length longer than the interelectrode spacing. These considerations lead to the selection of shaped-section, hard, straight elements. Since the nickel-based

*Registered Trademark of The International Nickel Co.

**Registered Trademark The Kanthal Corp.

TABLE 5-2. SUMMARY OF REQUIREMENTS, SELECTIONS AND ALTERNATES FOR APPLICATION TO CHARGED GRID CARBON FIBER SENSING INSTRUMENTS

ITEM, REQUIREMENTS, AND CRITERIA	EVALUATED AS USED, ACCEPTABLE OR REJECTED	IDENTIFIED ALTERNATES AND CANDIDATES
Grid Electrodes Material Alloys • Electrically Conductive • Thin adherent oxide (Corrosion resistant) + Ni-Cr Systems + Ni-Cr-Fe Systems	• 18Cr-8Ni-74Fe Utilized as Type 304 Stainless Steel • 80Ni-20Cr Acceptable as alternate - Cu, Temperature limitation - Al, Temperature limitation	• 62Ni-15Cr-23Fe for present temperatures • 25Cr-20Ni-55Fe as Type 310 Stainless • 77Ni-13Cr-10Fe for operation at 550°C • 25Cr-5Al-3Co-66Fe for operation above 550°C
Grid Electrodes • Structurally Stable under load + Simple beam support + Straight, hard + Resilient + Flow path 50% open	• Hypodermic Needle Tubing Utilized - Chemical mill or etch from sheet, showed sharp edges and poor surfaces in flow passages - Machining from sheet, residual stress distortions unacceptable	• Shaped wire hard drawn, straight annealed • Electrical discharge machining and polishing
Electrical Interconnection • Material compatibility with connection • Low Contact Resistance + Temperature compatible with operation + Technique does not anneal electrodes	• Spot weld utilized, two welds per electrode - Soft solder not compatible with operation temperature - Silver solder, concern for annealing - Furnace braze, Anneal Structure	• Electroformed Nickel bridge between electrodes • Mechanical crimp or swage to connection wire • Ultrasonic bond or pressure weld to connection wire • Integral if electrical discharge technique proves successful
	• Indicates a requirement or an acceptable alternate + Indicates a criteria or desirable feature - Indicates a rejected option	

TABLE 5-2. SUMMARY OF REQUIREMENTS, SELECTIONS AND ALTERNATES FOR APPLICATION TO CHARGED GRID CARBON FIBER SENSING INSTRUMENTS (CONCLUDED)

ITEM, REQUIREMENTS, AND CRITERIA	EVALUATED AS USED, ACCEPTABLE OR REJECTED	IDENTIFIED ALTERNATES AND CANDIDATES
Interelectrode Insulation • Insulator material dielectric remains above 10Kv/cm • Conforms to electrode shape + No voids between electrodes (Contaminant trap) + Non Absorbent Surface + Not triboelectric	Teflon and Sauereisen #8 Cement Utilized - Fired ceramics or fused glass anneals electrodes	• Moldable ceramics, and Cements • Machinable glasses • Extruded Insulators shaped conformal to the electrode • Flame sprayed ceramics MgO, Al₂O₃, ZrO₂
Support Structure • Stable over operating temperature range • Thermal Expansion compatible + Not triboelectric + Not Absorbent	Teflon utilized - Fiber reinforced epoxies not considered stable over temperature range	• Fired molded ceramics • Machinable Glasses • Low voltage charged metal plates
Assembly Tooling • Precision repeatable retention during buildup and joining operations	• Hand built wooden blocks and spacers cut from shim stock utilized - Machined grooves in Teflon, thin sections unstable during machining	• Precision drilled guillotines for grid holders • Cast in fusible alloy (woods, metal) during critical joining operations

alloys suitable for these applications will not precipitation harden, the configurations available relate to work-hardened straight drawn shapes. The manufactures of tubing and heater elements offer a range of shapes produced in such a fashion. If needed, special shapes can be obtained. Streamlined cross section stainless steel tube for aircraft instruments is an example of such a special need becoming a standard item. Conventional machining of the high-nickel alloys leaves high residual stresses in the surface layers of the material and thin sections deflect unpredictably. On the other hand, electric discharge machining does not alter the material, and these techniques are now well developed in the fabrication of instrumentation for aerodynamic testing (wind tunnels). This machining technique has worked well on the 80 Ni-20 Cr series alloys.

C. Electrical Interconnection

The thin adherent oxide coating which resists corrosion also resists joining for electrical contact. The conventional technique of heat joining in conjunction with a cleaning flux runs the risk of a local anneal to the work hardening which provides the structural integrity. The spot welding technique as utilized was developed for application to specialized instruments and should not be considered as generally available. The electrodeposition of nickel on Ni-Cr or Ni-Cr-Fe alloys can produce adherent, thick coatings. An electroformed bridge of nickel appears as a very attractive technique and would be suitable for operation at temperatures up to 500°C. Swaging or pressure bonding envisions an assembly technique which first joins a jumper lead to each electrode before assembly into a grid; the jumper leads would then be conventionally joined (silver solder, weld, etc.) to an exterior conductor. A grid structure formed from sheet stock eliminates the problem of interelectrode connections and, in addition, provides a positive positioning for one end of the grid.

D. Interelectrode Insulation

The integrity of the instrument depends upon the integrity of the interelectrode insulator. Fortunately, similar problems have been addressed and a range of insulating materials and cements have been developed for such applications. The Sauereisen series of cements were developed in response to these types of requirements. Moldable ceramics and machinable glasses represent a later series of developments. Some of the moldable ceramics are quite fibrous in the uncured form; a void-free fill between electrodes may present forming difficulties. The technology for flame spraying of ceramics has been developed for oxide or wear protection against high temperature corroding environments, and flame spray coatings are commercially available. A range of ceramic insulators appear as potential candidates; MgO , Al_2O_3 , ZrO_2 are all applicable. The use of BeO is not recommended; while BeO has the highest specific resistivity of any ceramic insulator, it will hydrolize in a hot,

moist atmosphere and thereby erode. The effect would be a concern for grids which had to operate at 500°C. Triboelectric adhesion to the interelectrode insulation becomes a consideration relative to electrical saturation. If a number of fibers adhere to the insulator so that the grid voltage cannot recover (the fiber-induced short accepts the recharging current), the cleaning process would be complicated and experience has shown such fibers adhere tenaciously. Prudence dictates an evaluation of such triboelectric adherence tendencies for any insulating material considered.

E. Supporting Structure

The construction and material selections for the supporting structure are premised upon non-interference with the flow passages. If the supporting structure includes the walls of the flow passages, then contamination, absorption, and triboelectric effects become considerations. If the instrument retains its present form as a continuous inline passage, then a metal liner charged to some intermediate voltage could retain the alignments of the fibers as they move through the instrument and prevent fallout or collection on the walls of the passages.

F. Assembly Tooling

The interelectrode spacing of the grids must be precisely controlled to assure the proper field strengths at all locations within the instrument. Tooling must effectively lock the grid elements in place throughout all of the assembly operations. Precision machining offers the best approach to the manufacture of holding and alignment fixtures. If the joining process for the electrodes or the application of insulation require harsh handling (flame spray, electrodeposition, etc.), the concept of casting into a low-melting alloy is a well established technique utilized within industry.

5.3 Operating Grid Cleaner

The grids which operate at field strengths of 10 Kv/cm exceed the fields applied in electrostatic precipitators. Cleaning of electrodes is a requirement in both cases. The method for cleaning may be application sensitive in that the dust and contaminants from a manufacturing operation could show adherence effects which differ from the particles emitted from incinerators. In the laboratory and flow facility evaluations, a back-blast of dry nitrogen would clean the flow passages between the grid wires. The design for a manufacturing facility should anticipate emissions from the handling of tow or the residues lofted during finishing operations, and even these effects may impose different requirements. The particulates emitted from municipal incinerators are usually well-characterized during the startup and initial operating phases of a new installation. Since electrostatic precipitators have become the principal technique for particulate control, their transmission characteristics would be an appropriate place to begin the study to determine the design requirements for a grid cleaning technique aimed at installation in an exhaust stack.

6.0 FLOW TEST AND CALIBRATION FACILITY

As a companion effort, a mobile flow test facility has been designed, built, and made operational to perform the evaluations and calibrations for the 5-grid sensor system. The facility employs a recirculating low speed wind tunnel to simulate flow conditions representative of industrial ventilating systems. The fiber dispensing equipment and the conductive fiber measurement equipment developed for the NASA has been installed as part of the total system (2). The principal features of the facility are shown in Figure 6-1; the descriptions, operating capabilities, and considerations for further development are described in the subsections which follow.

6.1 System Description

The mobile flow test and calibration facility has been installed in a mobile-home shell and consists of three major operating elements, plus a laboratory preparation area and small office for data reduction or planning support. The pertinent features of the facility are as follows:

A. The Recirculating Low Speed Wind Tunnel

The recirculating low speed wind tunnel provides a test section with a flow passage 63 cm square by 63 cm long. The shape of the inlet to the test section utilizes a long radius nozzle such that the flow velocities are uniform throughout the test section. The test section includes mounting brackets and hinged transparent walls such that instruments, tests units, and calibration rigs may be installed and operated. Air flow is induced by a 1.06 m diameter 6-blade fan, belt driven by two 1.5 hp variable speed pulsed-dc, electric motors. The entire installation has been configured to operate in an environment containing airborne fibers. All surfaces have been finished in a manner to aid cleaning, (e.g., hard, smooth-faced, minimum cracks or cavities, etc.). The design of the present system addressed the particular considerations of electrically conductive carbon fibers, therefore all electrical elements are concealed and protected. The facility can operate with any fibrous aerosol.

B. Fiber Dispenser System

The dispensing unit installed was originally designed to support in-chamber testing for exposures to airborne carbon fibers. In operation, the dispenser continuously chops a fiber tow into preselected lengths. Simultaneous with the cut, a gas jet disperses the fibers while a local updraft-flow-field separates the single fibers from clumps or multiples and then injects the single fibers into the entrance nozzle of the wind tunnel. In detail, a stepper motor geared to a pair of spring-loaded drive wheels precisely advances the tow for each cut. A solenoid-driven two-edged blade performs the shearing operation. A pulsed jet of

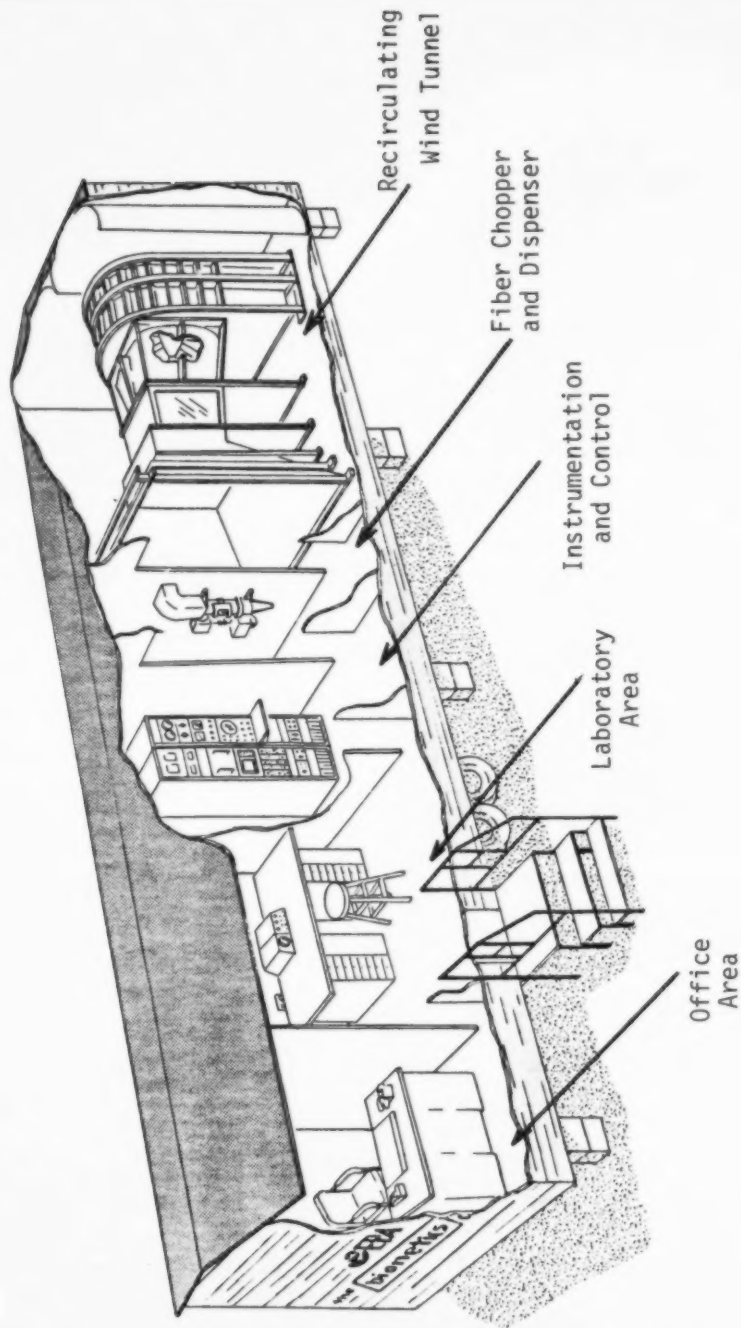


Figure 6-1. Mobile Flow Test Facility.

high pressure nitrogen disperses the chopped fibers. The vertical flow field utilizes a low-power vertical (industrial vacuum cleaner) air stream controlled to a velocity which exceeds the fall rate for single fibers but does not exceed the fall rate for multiples or clumps.

The system was designed to cut a tow containing 3000 structural grade carbon fibers each having an average diameter of 8 micrometers. Structural carbon fibers show a modest degree of graphitic microstructure. In subsequent operations, the unit has accepted tow with different counts, and fibers with all degrees of graphitization. In addition, the unit has successfully cut textile fibers, both natural and synthetic (cotton, wool, rayon, nylon, acrylic, etc.).

The vertical updraft dispensing system can be utilized to inject any type of fiber or any length distribution into the tunnel. A screen in the vertical duct, plus pulsed jets, provides a means for introducing a fiber source with any mix of materials or lengths, plus a capability to dispense and separate the fibers for injection into a flowing air stream.

C. Control and Instrumentation

The control and instrumentation presently installed permit the operation of the tunnel with an injected fibrous aerosol plus a method for measuring the population and length distribution of conductive fibers moving in the air stream. The flow rates are established by means of motor-speed control units. The velocities are sensed by a differential pressure measurement obtained from a pitot-static tube at the centerline of the test section. The chopper-dispenser control provides a means to select a length and a chopping rate compatible with both the materials being cut and the flow conditions in the tunnel.

The control of the dispensing and injecting velocities are both manual and visual. An illuminated viewing port in the injection duct provides the means for balancing the lifting velocity relative to the flow conditions in the tunnel and the fall velocities of the clumps within the ducts. This balance has to be visually verified for each flow velocity established within the tunnel. The static pressure in the closed recirculation system will vary slightly as a function of the flow velocity through the test section.

The conductive fiber measurement system was designed for use with a charge-transfer type of detection by an electrostatic field. This system senses the pulse triggered by a charge-transfer into a conductive fiber, and such pulses are related to the length of the fiber. The system applies the measurements of count and pulse to a multichannel spectral analyzer to provide data showing both the population and the length distribution.

D. Support Areas and Equipment

The shop and office areas have been configured to provide support to the operating sections. The shop area has illumination and power outlets sufficient to perform the types of activities associated with electronics troubleshooting and repair or maintenance of light equipment. The room has size sufficient to accommodate two work benches or up to six bays of electronic racks. The office area has room sufficient for a conference table or a desk plus a computer terminal. The mobile unit accepts regular household 220v ac fused to 100 amperes. The principal environmental control provided is a 5 hp domestic air conditioner.

6.2 Operating Capabilities of the System

The operating capabilities achieved within the facility are summarized in Table 6-1. The efforts to characterize the tunnel for achievable fiber populations showed a dependence upon both the velocity and the cut length of the fibers. These results are summarized in Table 6-2. The system does show consistent operation over a usable range for each parameter, and is capable of evaluating or calibrating instrumentation intended to sense or measure fibrous aerosols moving in ducts or stacks. The observations or conditions which present the current capabilities are described below. For three areas, the capabilities are less than the intended designs. The further actions required are presented in Section 6.3.

A. Test-Section Velocities

The distribution and range of usable velocities are considered satisfactory. The lower velocity limit correlates to the minimum expected in a ventilating duct. The lower limit shown relates to the fallout of fibers in the return passages. The return velocities are an order of magnitude below the velocities in the test section. At the lower test section limit, the return velocities reach 0.03 m/sec and these are the same as the fall velocity for carbon fibers in still air. Consequently, the low velocity test limit represents a condition for maintaining the population of the fiber at an acceptable level. Power to the drive fan sets the present upper limit. The tunnel will provide velocities up to 30 m/sec if sufficient power is provided.

B. Fiber Cutting

The fiber-cutting capabilities represent those obtained during chamber testing. The principal extension to experimental evaluations involved the successful cutting of textile-type fibers. The upper limit represents a practical consideration relative to the size of the wheels which advance the tow for each cut. The lower limit represents the capability of the cutter and is an area requiring development. The miss-cut lengths occur when fibers bend under the impact of the advancing blade and cause the blade to lift

TABLE 6-1. SUMMARY OF DEMONSTRATED OPERATING CAPABILITIES

<u>CAPABILITY</u>	<u>OPERATING RANGE</u>
1. Test Section	
a. Velocity, meters/sec	0.3 to 11.6
b. Variation	Less than 3 percent, worse case (low velocities)
2. Fiber Cutting	
a. Length, mm	0.2 to 20.0
b. Cuts, (per minute)	50 to 120
c. Miss cut lengths	Less than 5 percent worse case (short lengths)
3. Airborne Fiber Environment	
a. Population distribution, variation	Less than 10 percent
b. Residual after cleaning	Less than 1 percent
c. Operating time to equilibrium	Nominal 10 minutes
d. Maximum continuous operation achieved	2.0 hours
e. Carbon fiber ₃ population, fibers/meter	See Table 6-2
f. Population capability, other fibers	See 6.2.0

TABLE 6-2. MEASUREMENTS OF FIBER POPULATION FROM TUNNEL OPERATION

Length Range Measurement mm	Velocity 1.52 m/sec Count (Sampled Volume 4.85 m ³)	Velocity 3.05 m/sec Count (Sampled Volume 9.86 m ³)	Velocity 6.1 m/sec Count (Sampled Volume 11.8 m ³)
A. Cut length 0.2 mm			
0.1 - 0.2	40560	76720	36720
0.2 - 0.4	7360	3040	2800
0.4 - 0.8	720	720	320
0.8 - 1.6	0	0	0
1.6 - 3.2	0	0	0
B. Cut length 1.0 mm			
0.1 - 0.2	720	800	160
0.2 - 0.4	560	560	960
0.4 - 0.8	400	400	0
0.8 - 1.6	9360	5120	4400
1.6 - 3.2	80	80	320

NOTES:

- (1) Fiber populations are calculated in terms of fibers/meter³ based upon a microscope measurement of fibers collected on a filter. Count 6 Fields. Area correction is 80.
- (2) Cut length of 0.2 mm will produce a population in both length ranges.
- (3) Typical miss-cut, double length.
- (4) Short Fiber residual deliberately retained. Data expected to be erratic.
- (5) Population could be influenced by longer fiber break-up from impact with the drive fan.

slightly. The effect is most pronounced when cutting short (less than 1 mm) lengths from large-count tows. The effect usually appears as a double-length fiber.

C. Airborne Fiber Environments, General

The general considerations for the airborne fiber environment relate to repeatability of results and the operation of the tunnel. The environmental levels operationally achieved are discussed separately below.

Usable results from a test require a uniform distribution of fibers throughout the test section. This was achieved within a 10 percent variation; the variation had no discernable pattern for repetition. In designing the tunnel, the point for injecting the fibers was placed in the standing vortex which forms at the entrance to the nozzle. The vortex apparently provides the desired homogeneous mixing of the fibers with the flow. Usable data also require freedom from residual contamination. A thorough cleaning of the tunnel keeps residuals below one percent of the total population. In start up, the airflow rate must be established before the fibers can be injected. In a recirculating flow system, reaching an equilibrium population will require a finite time; 600 seconds (10 minutes) appeared as the normal time to reach a steady count rate. There is no limit to the time the tunnel can be run; however, long runs with continuous injection will complicate clean-up and begin to show trash-length fibers from collision impacts with the blades of the fan (impact velocities of 30 m/sec will cause fibers to break up). Chamber testing had established a practical upper limit for total exposure of 3.0×10^7 fibers sec/meter³ for any single test or evaluation. These conditions equate to a two₃hour immersion into a population of 4.2×10^7 fibers/meter³; such a population represents a limited upper capability for the tunnel in its present form.

D. Achievable Populations of Airborne Fibers

The data which supported the calibration of the 5-grid sensor provides a quantitative estimate for the present dispensing/injecting capability of the system. Table 6-2 summarizes the results based upon the collecting filter in the calibration test unit. The operational evaluation of the tunnel utilized two lengths of carbon fiber (0.2 mm and 1.0 mm long) collected at each of three velocities: 1.52 m/sec, 3.05 m/sec, and 6.1 m/sec. Since the data desired were intended to support calibration of the grids, some of the short fibers were allowed to remain in the tunnel so that there was a significant mix in length for the total population when operating with a 1 mm cut-length. The results of measurement show that the dispenser/injector operates more efficiently with shorter fibers. The gas jet separates the fibers more efficiently and the injecting system delivers more fiber into the airstream.

If the injection of fibers into the stream were independent of velocity, there would be an apparent reduction in population as velocity increased. The efficiency of the delivery system changes with velocity (better at low velocities) and the fallout has a complex relationship with velocity. These effects appear in the measurements summarized in Table 6-2. For 0.2 mm fibers the tunnel can assure a population of 2500 fibers/meter³ at velocities below 6 meters/sec. For fibers 1 mm long the assurance drops to 1000 fibers/meter³. Data from early operations with 3 mm fibers projects values of 500 fibers/meter³ as a present upper limit for long fibers.

In previous work, and during efforts to improve the cutting capability, a number of fibrous materials were chopped. The present system can accommodate any fiber which can be fed into the cutter in the form of a tow. The efficiency of the dispensing system will relate to the specific fiber being chopped. For textile-type fibers injected by means of the present system, a working population of 100 fibers/meter³ appears as a reasonable expectation.

6.3 Operating Improvements

The mobile flow-test facility has three limitations where improvements or developments are needed to achieve a maximum utilization. These elements and the actions required are described as follows:

A. Velocity Limitation

The present two-electric-motor fan-drive system cannot deliver full rated horsepower from both motors at the same time. The present units apply pulsed-dc to an armature running in the field of a permanent magnet. In operation, the motors will not stay in step at full load; a combined delivery of 2 horsepower appears as the upper limit. The recirculating tunnel should be able to deliver more than 20 meters/sec flow with a full 3 horsepower. A fully effective unit would utilize a 5 horsepower, voltage controlled, series-wound, dc motor. As a means for rectification and control, recent trade publications have identified a number of commercially available units which will provide controllable dc from a 220 volt ac source. The units employ silicon controlled rectifiers to simultaneously perform both the rectification and voltage control functions. Such a motor and control unit would be appropriate for installation in the present tunnel.

B. Increased Fiber Population in the Air Stream

A capability to assure a fiber population up to 3000 fibers/meter³ would provide a complete range for testing and evaluating any

instrument or sensing system. A new injection duct would overcome most of the present limitations. The installed duct has a square section flow-passage formed from sheet metal. An unacceptable portion of the lofted fibers are presently lost in the corner areas and this unit has proven difficult to clean between test exposures. A new unit formed with a circular cross section and a smooth interior (a glass-reinforced laminate) will overcome much of the present difficulty.

C. Extension of Chopper Capability to 0.1 mm

The present chopper will cut 0.2 mm lengths from a tow containing 3000 individual fibers. This appears as the limit for a blade held laterally by spring loading. Cutting shorter fibers consistently maybe achievable by using a tow with fewer fibers (less opportunity to deflect laterally), and by operating the blade in guides which have positive lateral constraints (no deflection from the direction of the cut). Such modifications are within the capability of a precision machine shop (e.g., instrument or tool maker). The present chopper has an installed capability to advance the tow in 0.1 mm increments, so no modification are needed to the feed control system.

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